CHAPTER
6 SUMMARY, CONCLUSION & FUTURE SCOPE

This chapter summarizes the work reported in this thesis, the major contribution, and some important conclusions. The scope for the future work is also presented at the end of the chapter.

6.1 Summary of the contributions

The BLDC motor drive is characterized by the electronic commutator which helps it to achieve speed control over wide speed ranges. The main flaws found with the BLDC motor operation are the requirement of position sensors for electronic commutation, high torque ripple with 2-Φ motor operation with trapezoidal back emf and quasi square wave currents, controller tuning for closed-loop operation the and the dynamic performance of the drive with closed-loop control. The investigation done using the literature survey came up with wide options in research ranging from design optimization, advanced control techniques, advanced controllers for controlling the BLDC motor drive.

The research work has focussed mainly on the control strategies for improved BLDC motor closed-loop control with 2-3ΦO and 3-ΦO to improve the dynamic and steady-state performance as compared to the 2-ΦO to target the following points

- Effective torque ripple mitigation
- Effective closed-loop speed control
- Reduced switching losses
- Effective utilization of the DC bus
- Minimum computational steps
- Reduced stator copper losses

In chapter 1, the issues related to the commutation torque ripple on BLDC motor performance with closed-loop control are investigated and various torque ripple mitigating techniques are reviewed. Based on the literature review, the research problem is formulated providing the road map to achieve the goal.

In chapter 2, the detailed analysis and development of torque ripple with the BLDC motor control with 2-ΦO is studied. The analysis shows that when the BLDC motor is operated with the conventional six-step operation, the mismatch in the slope of incoming and outgoing currents due to finite stator winding inductance results in the torque ripple in the commutation region. To prove this theoretical concept, the commutation logic for the operation of the 3-Φ inverter bridge using six-step 2-ΦO is developed using the HES output. The simulation is performed using MATLAB®/SIMULINK. The results show motor operation at different speeds and constant load conditions. It is observed that the BLDC motor with trapezoidal back emf and quasi square wave currents produces a significant commutation torque ripple. The detailed results of SSC at different speed and load condition is also provided in chapter 5. This theory provides the base for developing control techniques with improved motor steady-state and dynamic performance with closed-loop control. The results of the conventional SSC BLDC motor are provided in chapter 2 and chapter 5.

In chapter 3, A large torque ripple in the commutation region due to the mismatch in the slope of the incoming and outgoing current is imposed with the conventional SSC. To overcome this, a simple closed-loop HCCT based 2-ΦO of the motor is developed in MATLAB®/SIMULINK. The closed-loop control is implemented using the PI controller. A simple technique for tuning the PI controller using the motor transfer function is also discussed. The commutation logic for the 3-Φ inverter circuit required for energizing the three-phase stator winding is obtained using the hysteresis controller in which the motor actual currents are compared with the three reference currents with a specified narrow hysteresis band. Though this technique is providing 2-ΦO, but the simulation results show improved motor phase currents and reduced torque ripple as compared with the conventional SSC. The experimental verification is carried on a prototype BLDC motor using the STM32F407VG microcontroller with Cortex-M4 32 bit ARM controller. The hardware setup is tested by interfacing the hardware setup with the MATLAB®/SIMULINK WAIJUNG software using the HCCT. No complex coding is required using this platform which makes it easier to implement the control techniques. The same hardware setup validates the simulation results of the proposed control techniques provided in chapter 4 and chapter 5.

In chapter 4, the detailed analysis of various DTC techniques are discussed. This chapter proposes a two & three-phase operation(2-3ΦO) of BLDC motor drive with a MTSDTC technique with unipolar PWM switching method PWMON and ONPWM to reduce the commutation torque ripple as well as switching losses along with dead-band elimination. The concept of three-phase switching and null vectors is introduced in the commutation region. The operation of the BLDC motor with conventional 2ΦO and 2-3ΦO with SSDTC and TSDTC is provided with a phasor diagram and lookup tables. The lookup tables for inverter switching states during the conduction and commutation region for the proposed techniques are provided for the generation of the gate pulses. The simulation of the proposed techniques along with the conventional SSDTC, MSSDTC, and TSDTC technique is performed using MATLAB®/SIMULINK to prove the effectiveness of the proposed technique. The experimental results show the motor performance at low and high speeds under applied load conditions. Faster torque response is achieved with the proposed DTC technique with reduced torque ripple and switching losses using a two-level hysteresis controller. The closed-loop speed control is achieved with a PI controller. The fine-tuning of the PI controller provides improved dynamic performance of the BLDC motor.

In chapter 5, a modified sinusoidal pulse width modulation (MSPWM) technique is proposed to develop Maximum Torque Per Ampere (MTPA) by providing sinusoidal stator currents in synchronism with the back emf which is trapezoidal in nature, to reduce the commutation torque ripple. The closed-loop control is accomplished by providing a PI controller for a speed control loop, delta angle estimator, and rotor position estimator with low-cost hall sensors and shaft encoder. The flux control loop and torque control loop required for the DTC technique are eliminated with the proposed technique which reduces the computational steps. The proposed control technique requires only one PI controller which reduces the complexity as compared to the FOC with SVPWM technique. The complex calculation as required with the SVPWM technique for locating the reference space vector in space is eliminated using the proposed MSPWM technique. The proposed technique provides a higher DC bus utilization increasing the efficiency of the DC bus usage as compared to six-step control with torque ripple reduced by more than 50% at higher speeds. To justify the proposed MSPWM technique, the simulation is performed using MATLAB®/SIMULINK under varied speed and load conditions. The simulation results of the proposed MSPWM technique with 3-ΦO proves the effectiveness of the technique under varied speed and load conditions as compared to conventional SSC with 2-ΦO. The experimental results validate the simulation results of the proposed method with an improved motor performance at low and high-speed operation under different load conditions.

6.2 Conclusion

Based on the research objective and the summary of the work provided in the thesis regarding the proposed control techniques, the following conclusions are made:

- Effective torque ripple mitigation is achieved with the proposed MTSDTC ONPWM control with 2-3ΦO as compared to other DTC techniques.
- Reduced switching losses are obtained using the proposed MTSDTC PWMON and ONPWM control with 2-3ΦO as compared with the conventional TSDTC technique with 2-3ΦO. This will result in the improvement of the overall drive efficiency and motor performance.
- Effective closed loop speed control is achieved with the proposed MTSDTC ONPWM and PWMON control techniques with 2-3ΦO.
- It is observed that the commutation torque ripples are considerable in conventional six-step operation while the commutation torque ripples are almost reduced to PWM torque ripple by the proposed MSPWM technique with 3-ΦO.
- Effective closed-loop speed control is achieved with the proposed MSPWM technique using a single PI controller with an improved dynamic and steady-state performance of the BLDC motor.
- Effective utilization of the DC bus is achieved with increased efficiency of DC bus voltage usage with the proposed MSPWM technique (3ΦO) as compared to conventional SSC (2-ΦO).
- Minimum computational steps are required with the proposed MSPWM technique (3ΦO) as compared to the SVM-based DTC and SVM-based FOC control techniques.
- Reduced stator copper losses are achieved with the proposed MSPWM technique (3ΦO) with sinusoidal stator currents in phase with the trapezoidal back emf as compared to the other control techniques discussed with 2-ΦO and 2-3ΦO with quasi square wave currents in phase with the trapezoidal back emf. This results in improved motor efficiency and overall drive performance.

- The simulation results of the proposed MTSDTC ONPWM, MTSDTC PWMON and MSPWM techniques are validated by the experimental results.

6.3 Future scope

The proposed control techniques used for closed-loop control presented in the thesis still have a scope to work with. The future scope are listed below:

- In chapters 4, the proposed DTC techniques can be implemented with position estimation algorithm for BLDC motor control to overcome the flaws with sensored drives. This will result in reduction of the overall cost of the drive.
- In chapter 4, the proposed DTC techniques with 2-3-ΦO can be extended to 3-ΦO using pseudo-dq transformation to extend the work to flux control. This will provide improved motor performance and increase the overall efficiency of the drive.
- In chapters 4, and 5, the proposed DTC control techniques and MSPWM technique can be implemented using fuzzy logic controller instead of the conventional PI controller used in this work.
- In chapter 5, a position estimation algorithm based MSPWM technique with 3-ΦO can be implemented with sinusoidal stator phase currents in phase with the trapezoidal back emf. This will eliminates the requirement of an expensive encoder for continuous position detection and reduce the overall cost of the drive.